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SUPERSYMMETRY AT THE LINEAR COLLIDER

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If supersymmetry (SUSY) is realized at the electroweak scale, its underlying structure and breaking mechanism may be explored with great precision by a future linear e^+e^- collider (LC) with a clean environment, tunable collision energy, high luminosity polarized beams, and additional e^-e^-, $e\gamma$ and $\gamma\gamma$ modes. In this report we summarize four papers submitted to the ICHEP04 conference about the precise measurements of the top squark parameters and $\tan\beta$, the impacts of the CP phases on the search for top/bottom squarks, the Majorana nature and CP violation in the neutralino system, the implications of the SUSY dark matter scenario for the LC experiments, and the characteristics of the neutralino sector of the next–to–minimal supersymmetric standard model at the LC.

1 Introduction

Weak–scale SUSY has its natural solution to the gauge hierarchy problem, providing a *stable* bridge between the electroweak scale and the grand unification or Planck scale[1], with which the roots of standard particle physics are expected to go as deep as the Planck length of 10^{-33} cm. It is then crucial to probe SUSY and its breaking with great precision at a future e^+e^- linear collider (LC)[2] as well as the large hadron collider (LHC)[3] for a reliable grand extrapolation to the Planck scale[4].

In this report we summarize four papers submitted to the ICHEP04 conference about SUSY phenomenology at the LC.

2 Precise determinations of SUSY parameters

If SUSY is realized at the electroweak scale, the LC experiments can be performed in the SUSY sector with high precision. In this section, I report on two related works submitted to this conference.

2.1 Top squark mass determinations

The study of the top squarks is of particular interest, since the lighter top squark is likely to be the lightest squark in a SUSY theory due to the significant mixing between two top squark weak eigenstates.

The recent work in Ref. [5] compares four methods for measuring the top squark mass $m_{\tilde{t}_1}$ at the LC. Two conventional methods rely on an accurate measurement of the production cross section with beam polarization at one fixed energy and through threshold scans of the cross section[a]. The other two methods for measuring the top squark mass use information from two measured charm jets with large missing energy due to the unobserved neutralino $\tilde{\chi}^0_1$.

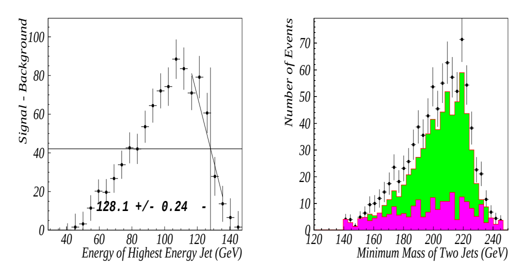

Figure 1. Examples of measuring the maximum jet energy end point (left) and the minimum mass of two jets (right).

Two end points of the charm energy spectrum of $\tilde{t}_1 \to c\tilde{\chi}^0_1$, flat at the parton level, contain information on $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1}$. In practice, this ideal situation is distorted by resolution effects as demonstrated in the left panel of Fig. 1 for the SPS5 point[6]. When

[a] The first method allows us to measure the mixing angle $\theta_{\tilde{t}}$ as well as the top squark mass.

$m_{\tilde{\chi}_1^0}$ is known the minimum allowed mass distribution of the two charm jets in an event can be used to measure $m_{\tilde{t}_1}$ with the accuracy of the order of 1 GeV with $\int \mathcal{L}dt = 500$ fb^{-1} at $\sqrt{s} = 500$ GeV, comparable to that from the other methods, as shown in the right panel of Fig. 1.

2.2 *A new* $\tan\beta$ *determination method*

Many observables, in the chargino/neutralino sector[7,8] for instance, involve only $\cos 2\beta$ and thus are quite insensitive to $\tan\beta$ for large values. On the contrary, for large pseudoscalar Higgs mass the heavy H/A Higgs couplings to down-type fermions are directly proportional to $\tan\beta$ if the parameter is large so that they are highly sensitive to its value[9]. Also the down–type couplings of the light h Higgs boson in the MSSM are close to $\tan\beta$ if M_A is moderately small. Based on these observations, we show that $\tau\tau$ fusion to Higgs bosons at a photon collider[10] can provide a valuable method for measuring $\tan\beta$.

For large $\tan\beta$, all the Higgs bosons Φ $(= H, A, h)$ decay almost exclusively [80 to 90%] to a pair of b quarks so that the final state consists of a pair of τ's and a pair of resonant b quark jets. Two main background processes – the $\tau^+\tau^-$ annihilation into a pair of b-quarks via s–channel γ/Z exchanges and the diffractive $\gamma\gamma \to (\tau^+\tau^-)(b\bar{b})$ events with the pairs scattering off each other by Rutherford photon exchange – can be suppressed strongly by choosing proper cuts[10].

The left panel of Fig. 2 shows the exact cross sections for the signals of H and A Higgs–boson production in the $\tau\tau$ fusion process with $E_{\gamma\gamma} = 600$ GeV, together with all the background processes with appropriate experimental cuts. As shown in the right panel of Fig. 2 $\tau\tau$ fusion to the light Higgs boson h with $E_{\gamma\gamma} = 400$ GeV can also be exploited to measure large $\tan\beta$ for moderately small M_A. For h production, the mass parameters are set to $M_A \sim 100$ GeV and

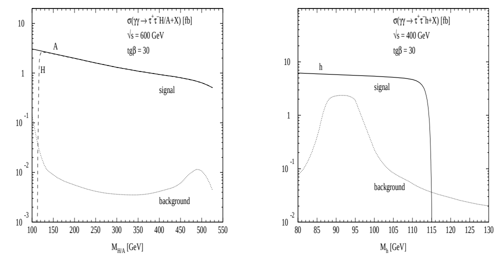

Figure 2. The cross sections for the production of the H/A (left) and h (right) Higgs bosons in the $\tau\tau$ fusion process at a $\gamma\gamma$ collider for $\tan\beta = 30$. Also shown is the background cross section with experimental cuts. $\sqrt{s}$ denotes the $\gamma\gamma$ collider c.m. energy.

$M_h = 100$ GeV. The channels h/A and H/A are combined in the overlapping mass ranges in which the respective two states cannot be discriminated. Since in the region of interest the $\tau\tau$ fusion cross sections are proportional to $\tan^2\beta$ and the background is small, *the absolute errors* $\Delta\tan\beta$ *are nearly independent of* $\tan\beta$, varying between ~ 0.9 and 1.3 for Higgs masses away from the kinematical limits for the integrated luminosity of 200/100 fb^{-1} for the high/low energy option.

3 CP violation in the MSSM

Many SUSY parameters in the MSSM are in general complex, in particular the higgsino mass parameter μ, the gaugino mass parameters $M_{1,2,3}$ and the trilinear scalar coupling parameters A_f of the sfermions $\tilde{f}$[b].

Not only the CP–violating observables such as electric dipole moments[11] and triple products of momenta and polarization vectors[12] but also the CP–conserving observables like cross sections and decay widths depend on the phases of the complex parameters. Recently there have been a lot of interesting works on the direct and indirect observations of CP violation in the SUSY particle sectors[11,12,13] and the Higgs boson sector[14,15]

[b]The SU(2) gaugino mass parameter M_2 can be set real and positive after an appropriate redefinition of the fields.

of the CP–noninvariant version of the MSSM. In this section we review two relavant works submitted to this ICHEP04 conference.

3.1 Impacts of CP phases on the top/bottom squark searches

The phases of the trilinear parameter A_f and the higgsino mass parameter μ are involved directly in the squark mass matrices and the squark–Higgs and squark–quark–gaugino/Higgsino couplings. As a result, the squark–pair production cross sections and squark decay widths are strongly affected by the phases. In Ref. [16] the authors have studied the effects of the phases of the parameters $A_{t,b}$, μ and M_1 on the phenomenology of the top/bottom squarks, which can be significant due to large Yukawa couplings.

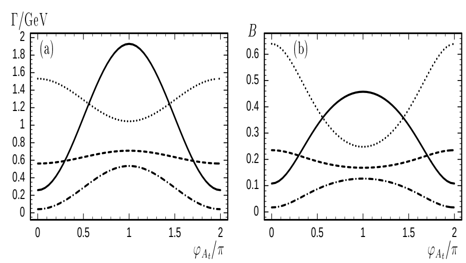

Figure 3. The ϕ_{A_t} dependence of the partial decay widths (left) and branching ratios (right) for the decays $\tilde{t}_1 \to \tilde{\chi}_1^+ b$ (solid), $\tilde{t}_1 \to \tilde{\chi}_1^0 t$ (dashed), $\tilde{t}_1 \to \tilde{\chi}_2^+ b$ (dash–dotted) and $\tilde{t}_1 \to \tilde{\chi}_2^0 t$ (dotted) for the parameter set described in the text.

As clearly shown in Fig. 3 with a typical parameter set, the partial widths (left) and branching ratios (right) for the top squark decays depend strongly on the CP phase ϕ_{A_t}, implying the importance of taking into account the impacts of the CP phases in searching for SUSY particles.

3.2 Majorana nature and CP violation in the neutralino system

It is a unique SUSY test to establish the Majorana nature and CP properties of neutralinos. Here, we describe two methods for probing the Majorana nature and CP violation in the neutralino system.

With the neglected SM fermion masses both the processes, $e^+e^- \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$ and $\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 f\bar{f}$, can effectively be regarded as processes of a vector current exchange between two neutralinos. In the CP invariant case, the neutralino $\{ij\}$ pair production and the decay $\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 V$ through a vector current satisfy the CP relations

$$1 = \pm\eta^i\eta^j\ (-1)^L \tag{1}$$

for static neutralinos, with $\eta^i = \pm i$ the intrinsic $\tilde{\chi}_i^0$ CP parity and L the orbital angular momentum of the produced pair $\{ij\}$ and of the final state of $\tilde{\chi}_j^0$ and V, respectively. Therefore, in the CP invariant case, if the production of a pair of neutralinos with the same (opposite) CP parity is excited slowly in P waves (steeply in S waves) near threshold, then the $\tilde{\chi}_i^0$ to $\tilde{\chi}_j^0$ transition is excited sharply in S waves (slowly in P waves) near the end point of the fermion invariant mass.

In the CP noninvariant case the orbital angular momentum is no longer restricted by the selection rules (1). Consequently, CP violation in the neutralino system can be signalled by (a) the sharp S–wave excitations of the production of three non–diagonal $\{ij\}$, $\{ik\}$ and $\{jk\}$ pairs near threshold[8,17] or by (b) the simultaneous S–wave excitations of the production of any non–diagonal $\{ij\}$ pair in e^+e^- annihilation near threshold and of the fermion invariant mass distribution of the neutralino three–body decays $\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 f\bar{f}$ near the kinematical end point[18]. Note that even the combined analysis of the lighter neutralino $\{12\}$ pair production and the associated decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 f\bar{f}$ enables us to probe CP violation in the neutralino system.

In addition, if the two–body decays $\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 Z$ are open and not suppressed, the Z polarization reconstructed via leptonic Z–boson decays with great precision allows us to probe the Majorana nature and CP violation in the neutralino system[19].

4 Implications for LC experiments of the SUSY DM scenario

The DM constraints from the recent WMAP results[20] on the SUSY parameter space imply, for many of the retained working points, a small mass difference $\Delta m \leq m/20$ between the tau slepton $\tilde{\tau}_1$, and the LSP mass for the so–called *co–annihilation mechanism*. The amount of DM depends critically on $m_{\tilde{\tau}_1}$ itself as well. This means that *the proper justification of the co–annihilation mechanism requires an extremely precise measurement of* $m_{\tilde{\tau}_1}$ *and* $m_{\tilde{\chi}^0_1}$.

In this co–annihilation scenario the detection and the mass measurement of the tau slepton through threshold scan is, however, challenging because of a potentially very large background due to the four fermion final states, the so–called $\gamma\gamma$ background.

A recent work in Ref. [21] has shown with a detailed analysis that a forward veto to remove the $\gamma\gamma$ background down to very small angles is essential to reach an almost background free result, adequate to achieve the accuracy implied by the post–WMAP generation in a model independent analysis. It has also pointed out the reduction of efficiency of this veto by a non–zero crossing angle between electron and positron beams and due to the very large overlaid background produced by beam–beam interaction hitting the very forward electromagnetic calorimeter.

5 NMSSM neutralino sector

The NMSSM superpotential[22,23] with an iso–singlet Higgs superfield $\hat{S}$ in addition to the two Higgs doublets superfields $\hat{H}_{u,d}$ reads

$$W = W_Y + \lambda \hat{S}(\hat{H}_u \hat{H}_d) + \frac{1}{3}\kappa \hat{S}^3 \qquad (2)$$

where W_Y denotes the MSSM Yukawa components. The two dimensionless parameters λ and κ are less than 0.7 with $\kappa < \lambda$ favored at the electroweak scale if they remain weakly interacting up to the GUT scale[22].

The singlet superfield adds an extra higgsino to the MSSM neutralino spectrum, called a *singlino*, resulting in five neutralinos. We denote the singlino dominated neutralino $\tilde{\chi}^0_5$, with $\tilde{\chi}^0_{1-4}$ denoting the other four neutralinos in order of ascending mass.

In the above preferred scenario, the singlino dominated neutralino is the lightest neutralino (and the LSP) with a mass of approximately $\mu_\kappa \equiv 2\kappa\langle S\rangle$ so that it will be copiously produced at the LHC in squark and gluino cascade decays. A very decoupled state with low λ can give rise to macroscopic flight distances of order a μm and order a nm for the decays $\tilde{\chi}^0_1 \to \tilde{\chi}^0_5 l^+ l^-$ and $\tilde{l}_R \to \tilde{\chi}^0_5 l$ with $\mu_\lambda (\equiv \lambda v/\sqrt{2}) = 1$ GeV, respectively. With the integrated luminosity of 1 ab^{-1}, large event rates of order 10^3 are expected for production of $\tilde{\chi}^0_5$, $\tilde{\chi}^0_1$ or $\tilde{\chi}^0_3$ with $\tilde{\chi}^0_5$ for $\mu_\lambda > 30$ GeV. These characteristic signatures will allow us to distinguish the NMSSM from the MSSM experimentally.

6 Conclusions

As evident from the examples discussed above and in a lot of collective studies[2], if a few sparticles are kinematically accessible, the LC will enable us to make model–independent measurements of a host of SUSY parameters and to reveal a variety of phenomenological implications.

The highest possible precision to be provided by the LC ($\otimes$ LHC) experiments[24] is essential to reveal the SUSY structure and breaking mechanism through a reliable grand extrapolation to the Planck scale. This should definitely be one of the most important aspects of the LC physics potential.

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